Defence Research and Development Canada
Recherche et développement pour la défense Canada

DEFENCE R&D DÉFENSE

Recent advances in the remote sensing of radiological materials by passive FTIR radiometry

2005-2006 summary report for the Canadian Safeguards Support Program of the Canadian Nuclear Safety Commission

E. Puckrin
J.-M. Thériault
DRDC Valcartier

Defence R&D Canada – Valcartier

Technical Note
DRDC Valcartier TN 2006-120
May 2006

Canada

Recent advances in the remote sensing of radiological materials by passive FTIR radiometry

2005-2006 summary report for the Canadian Safeguards Support Program of the Canadian Nuclear Safety Commission

E. Puckrin
J.-M. Thériault
DRDC Valcartier

Defence R&D Canada – Valcartier

Technical Note

DRDC Valcartier TN 2006-120

May 2006

Author

Eldon Puckrin

Approved by

Jean-Marc Garneau

Section Head, Optronic Surveillance

Abstract

Over the past year DRDC Valcartier has continued to investigate the feasibility of using passive standoff FTIR radiometry for the detection of radiological materials. Previously, we have shown that a large number of radiological materials have an infrared signature in the 8–14 μm thermal infrared region, including several oxides of uranium and cobalt. Based on the positive results of a number of ground-based measurements and simulations using the MODTRAN4 atmospheric transmission model, it was decided that a measurement campaign should be attempted using an airborne HSI sensor.

The AIRIS sensor, developed by DRDC Valcartier and installed in a Convair 580 aircraft, was used to measure several radiological compounds from an altitude of 1 km during a trial at DRDC Suffield in July 2005. The ARIS sensor was used in conjunction with two different telescopes; one resulting in high-resolution spatial images and the other resulting in low-spatial resolution images. Unfortunately, the former configuration did not function correctly during the trial, and only the low-resolution images were captured by AIRIS. An additional six months is required for the analysis of these images to be completed before it will be known if the HSI sensor was successful in detecting and identifying the radiological compounds. Ground-truth data collected during the trial at DRDC Suffield will be used in the image analysis process.

Future work is planned for 2006/2007 that may involve an additional trial with the AIRIS HSI sensor.

This page intentionally left blank.

1. Introduction

Passive standoff detection by Fourier-transform infrared (FTIR) radiometry has become a relatively mature and reliable method for the identification and measurement of chemical vapours emitted from stacks.[1-4] Recently, it has also been shown to be a potentially valuable tool for measuring biological warfare agents[5,6] and surfaces contaminated with CW agents.[7] Therefore, passive standoff detection by FTIR radiometric techniques may have an important role in detecting and identifying chemical and biological (CB) hazards on the battlefield and as a counter-terrorism measure. In addition to chemical and biological agent hazards, there is the possibility of a release of nuclear material at a nuclear power plant, during the transportation of radioactive materials, or by terrorist activity, which could result in widespread radioactive contamination over populated regions.

Previously, we have shown that some materials such as UO_2, UO_3, U_3O_8, CoO, Co_2O_3, ThO_2, CsI, SrO, I_2O_5 and La_2O_3 have absorption features in the thermal infrared region, and that these materials may potentially be detected by passive FTIR radiometry.[8,9] Thorough several studies based on simulations performed with the MODTRAN4 transmission code[10] it has also been shown that many of these materials have the potential to be detected remotely from an airborne platform using passive standoff detection. Initial measurements in the filed of SrO and CoO at standoff distances of 50 m have also been successful in demonstrating the remote detection of radiological materials.[9]

As a result of this previous work, it has become evident that airborne measurements of radiological materials should be undertaken. To achieve this goal, an experiment was planned for July 2005 at DRDC Suffield that included the measurement of four radiological materials using a passive HSI sensor onboard an aircraft at an altitude of 1 km. The sensor used was the Airborne Infrared Imaging Spectrometer (AIRIS) developed by DRDC Valcartier. It was installed in the Convair 580 aircraft operated by the National Research Council (NRC). A summary of this airborne study is the focus of this report.

2. Detection principles and phenomenology

A passive long-wave infrared standoff sensor functions by exploiting the temperature difference *(ΔT)* that exists between the target scene and the background scene. If the target is warmer than the background, then the spectrum of the target chemical will be measured as an emission feature in the spectrum recorded by the sensor. Conversely, if the target is colder than the background, then the target chemical spectrum will be measured as an absorption feature. When a target consisting of a solid powder is present on a surface, ΔT is zero since the background (surface) and the powder are in contact. However, if the radiation from an external hot or cold source is reflected from the surface, then it is possible to observe the spectrum of the powder. In outdoor environments, the radiation from the cold sky provides a high surface-to-sky temperature difference that yields favourable detection possibilities. The radiative transfer associated with the detection of powdered targets is outlined below.

The radiative transfer intervening at a surface can be understood from a simple physical argument. A diagram is presented in Fig. 1 that defines the parameters used to evaluate the radiance emanating from a clean surface and one contaminated with a powder; both are exposed to an outdoor environment. For a clean surface having a reflectance R_o, the spectral radiance measured at the sensor contains two components, i.e. the emitted radiance from the surface, $B(1- R_o)$, and the cold sky radiance reflected by the surface, $L_{down} R_o$. The parameter, L_{down}, represents the downwelling radiance from the sky and B is the Planck radiance evaluated at the temperature (T) of the surface that is given by

$$B = \left(\frac{1.191 \times 10^{-12} \nu^3}{e^{\left(\frac{1.439\nu}{T}\right)} - 1} \right) \tag{1}$$

where ν is the wavenumber in cm^{-1}, and B is in W/cm^2 sr cm^{-1}. Adding these two radiance components, $B(1- R_o)$ and $L_{down} R_o$, yields an expression for the radiance of the uncontaminated surface that is given by

$$L_{clean} = B - R_o \left(B - L_{down} \right) \tag{2}$$

Similarly, for a contaminated substrate consisting of a powder with a reflectance R_{cont}, as shown in Fig. 1, the spectral radiance measured by the sensor is given by,

$$L_{cont} = B - R_{cont} \left(B - L_{down} \right) \tag{3}$$

A quantity of interest to study the perturbation effects of a contaminant on a surface is the differential spectral radiance (ΔL), which is the radiance difference (L_{cont} -L_{clean}) obtained by subtracting Eq. (2) from Eq. (3),

$$L_{cont} - L_{clean} \equiv \Delta L = (R_o - R_{cont})(B - L_{down}) \qquad (4)$$

Inspection of Eq. (4) reveals some simple facts concerning the sensitivity for detecting surface contaminants by passive spectral radiometry. First of all, the radiance difference is proportional to the reflectance contrast ($R_o - R_{cont}$), indicating that a highly reflecting surface results in an increased sensitivity for detection. Secondly, the radiance difference is proportional to the radiative contrast between the Planck surface radiance and the downwelling sky radiance, ($B - L_{down}$). Since the downwelling radiance increases with cloud cover, which in turn results in a decrease in the radiative contrast, the best detection possibilities are obtained for clear sky conditions where L_{down} is a minimum.

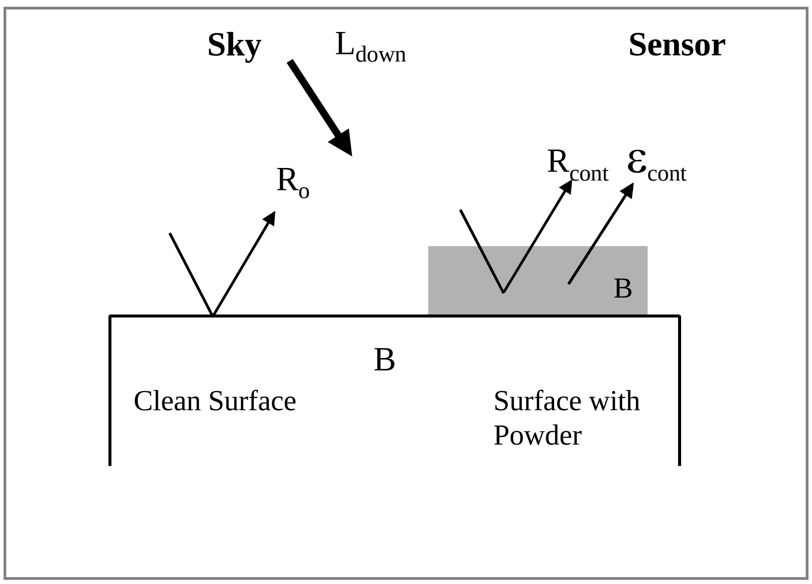

Figure 1: Diagram and parameters used to evaluate the radiance of a clean surface and a surface covered by a powdered contaminant.

3. AIRIS Sensor

The AIRIS sensor is a hyperspectral imaging (HSI) system operated from the National Research Council - Flight Research Laboratory (NRC-FRL) Convair 580 aircraft. It can also be adapted to other aircraft platforms. As a nadir system, AIRIS combines broadband imagery and hyperspectral sensing. It consists of three broadband imagers: one operating in the visible region and two in the IR (one in the 3-5 µm and one in the 8-12µm regions). These are coupled to the narrow field of view imaging spectrometer which contains two detector channels; one optimized for the mid-near IR region (2.0 – 5.3 um) and one optimized for the longwave IR region (8 – 12 um). The spectrometer detectors were liquid nitrogen cooled and consisted of an InSb (Indium & antimonite) and a MCT (Mercury Cadmium Telluride) 8x8 element detector arrays. The spectral resolution was variable between 1-16 cm^{-1}. The system operated in two distinct modes of operation using either a narrow or a wide field of view telescope. The telescopes were not interchangeable while in flight but were interchanged on the ground within approximately 2 hours.

The AIRIS system was operated by a two-person crew and could support continuous acquisition for up to a four-hour flight. It is equipped with a tracking system, which allows geo-referenced, pre-selected and manual acquisition of targets within a grid 64 times the field of view of each of the spectrometer detector arrays. A description of the field of view characteristics of AIRIS is shown in Table 1. Figures 2 and 3 show pictures of the AIRIS system installed in the Convair aircraft.

TABLE 1. AIRIS TELESCOPES FIELD OF VIEW

Altitude	***1Km***	***2Km***	***3Km***	***4Km***	***5Km***
	(3280ft)	***(6560ft)***	***(9840ft)***	***(13120ft)***	***(16400ft)***
NFOV (9X)					
Pixel area (m)	1.2 x 1.2	2.4 x 2.4	3.6 x 3.6	4.8 x 4.8	6.0 x 6.0
Max Time above target at 100m/s	0.76 s	1.52 s	2.28s	3.05 s	3.81 s
WFOV (3X)					
Pixel area (m)	3.6 x 3.6	7.1 x 7.1	10.7 x 10.7	14.3 x 14.3	17.9 x 17.9
Max Time above target at 100m/s	2.28 s	4.57s	6.85 s	9.14 s	11.42 s

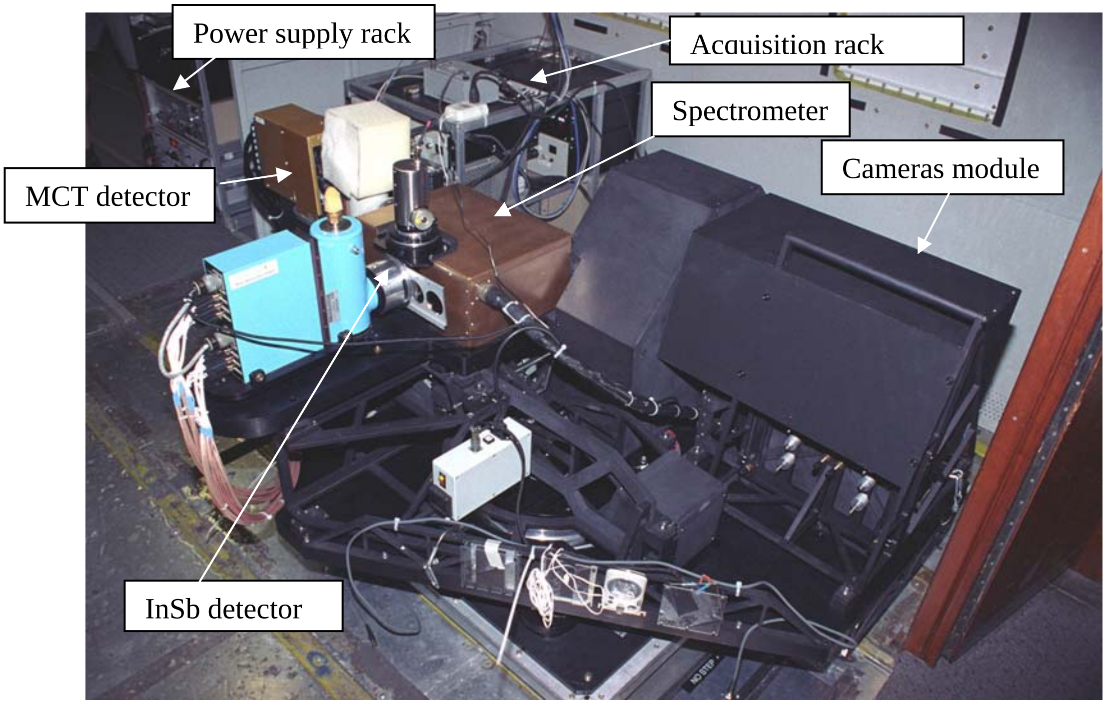

Figure 2. AIRIS and acquisition rack

Figure 3: Convair aircraft showing the window mounted in the bottom of the plane to allow nadir measurements by the AIRIS sensor.

4. Experimental Measurement Plan

The measurement campaign was carried out 14 July 2005 at DRDC Suffield. The radiological targets consisted of cobalt oxide (mixture of CoO and Co_2O_3), cesium chloride ($CsCl_2$), iodine oxide (I_2O_5) and strontium oxide (SrO). Initially it was planned to include two uranium oxides (UO_2 and U_3O_8); however, high wind conditions precluded their use for safety reasons. The four targets, which each measured 2m × 2m, were positioned in a linear array as shown in Figure 4 with a separation of 150 m between each target. Photographs of the four materials are shown in Figure 5.

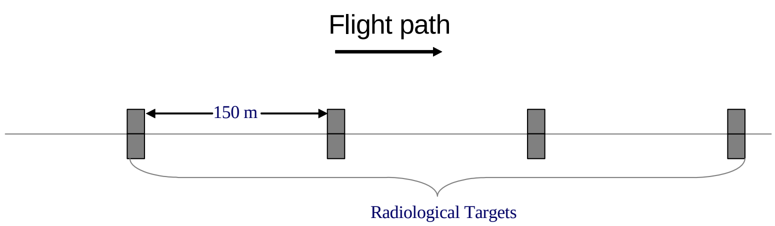

Figure 4. Array of four radiological targets aligned along Convair flight path

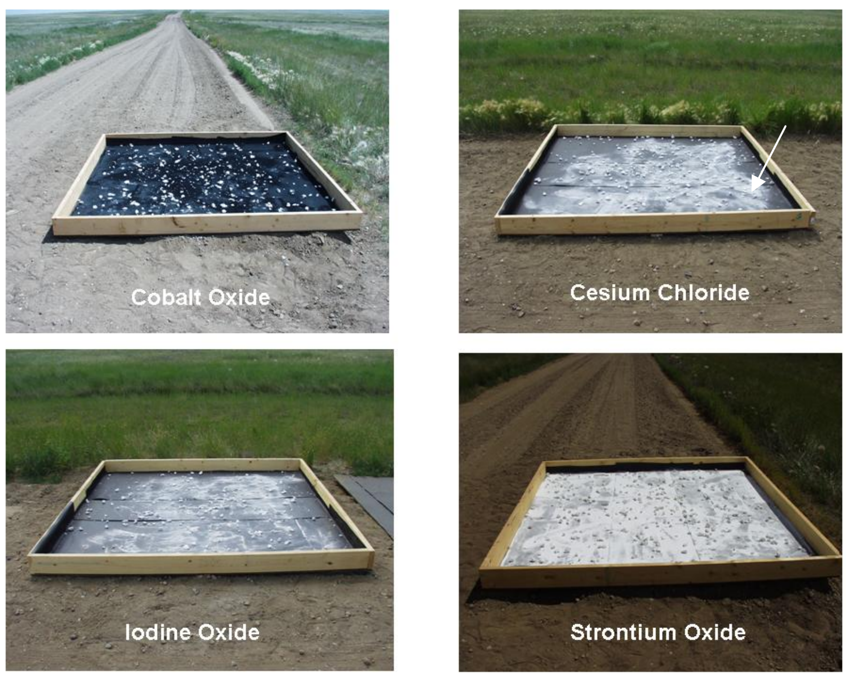

Figure 5. Photograph of the four radiological targets used in the field trial

5. Results and Discussion

An example measurement of a broadband image of the radiological targets obtained with the AIRIS sensor from an altitude of 1 km is shown in Figure 6. The image shows the scene as the aircraft approaches the ground targets to the right.

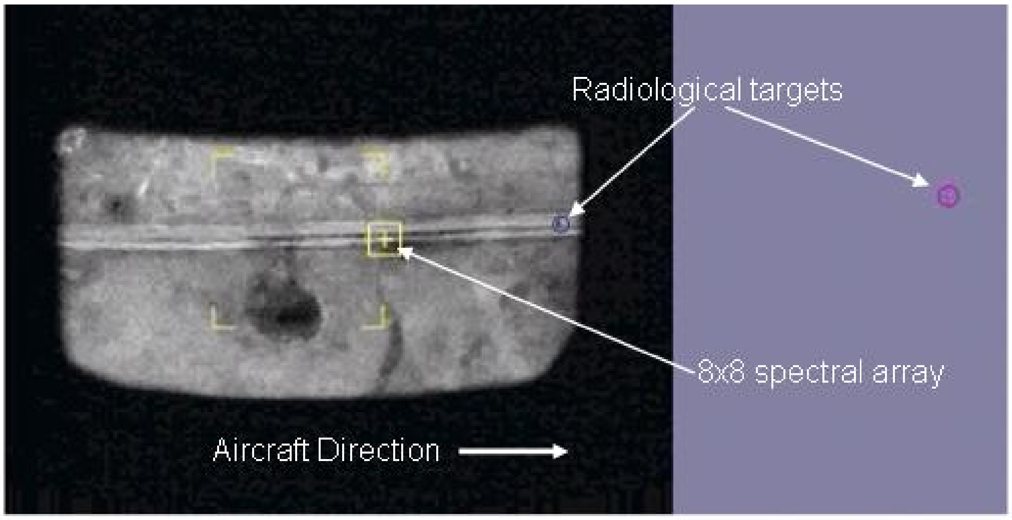

Figure 6. Image measured from the Convair aircraft showing approaching ground targets

This trial represented the first time that the MCT detector had been implemented on the AIRIS sensor. Unfortunately, due to a configuration problem between the narrow field of view telescope and the MCT detector array that was discovered during the trial, it was not possible to obtain spectral measurements in the 8-12 μm band at high spatial resolution (i.e., 1.2 m). The MCT configuration with the wide field of view telescope was completely functional, which provided spectral measurements at a spatial resolution of 3.6 m. Since the targets measured only 2 m it is unclear whether the signature of the radiological materials will be detected with the wide field system. Analysis of the airborne spectra is currently underway; however, results are not yet available. It is expected that an additional six months will be required to complete this task.

As in the case of the trial[9] held at DRDC Valcartier in June 2004, ground-truth measurements of the radiological materials were carried out at DRDC Suffield to compare with the AIRIS results. The ground-based FTIR measurements were performed in a similar way as discussed previously.[9] An example of a ground-based spectral measurement for cobalt oxide (CoO and Co_2O_3 mixture) is presented in Figure 7. The top figure represents the calibrated radiance measurement (black curve) along with the radiance spectrum simulated for a blackbody at a temperature of 313 K (red curve). Subtracting the two spectra yields the differential radiance (bottom

figure), which cancels out the large blackbody-like contribution. A simulation of the differential radiance of cobalt oxide (red curve) was performed using the MODTRAN 4 radiative transfer model[10] and the reflectance signature of cobalt oxide measured in the laboratory. A comparison between the two differential spectra clearly shows the presence of the cobalt oxide fingerprint, as indicated by the arrows. Ground-truth data such as this will be used to help identify the radiological signatures in the wide-field airborne spectral measurements.

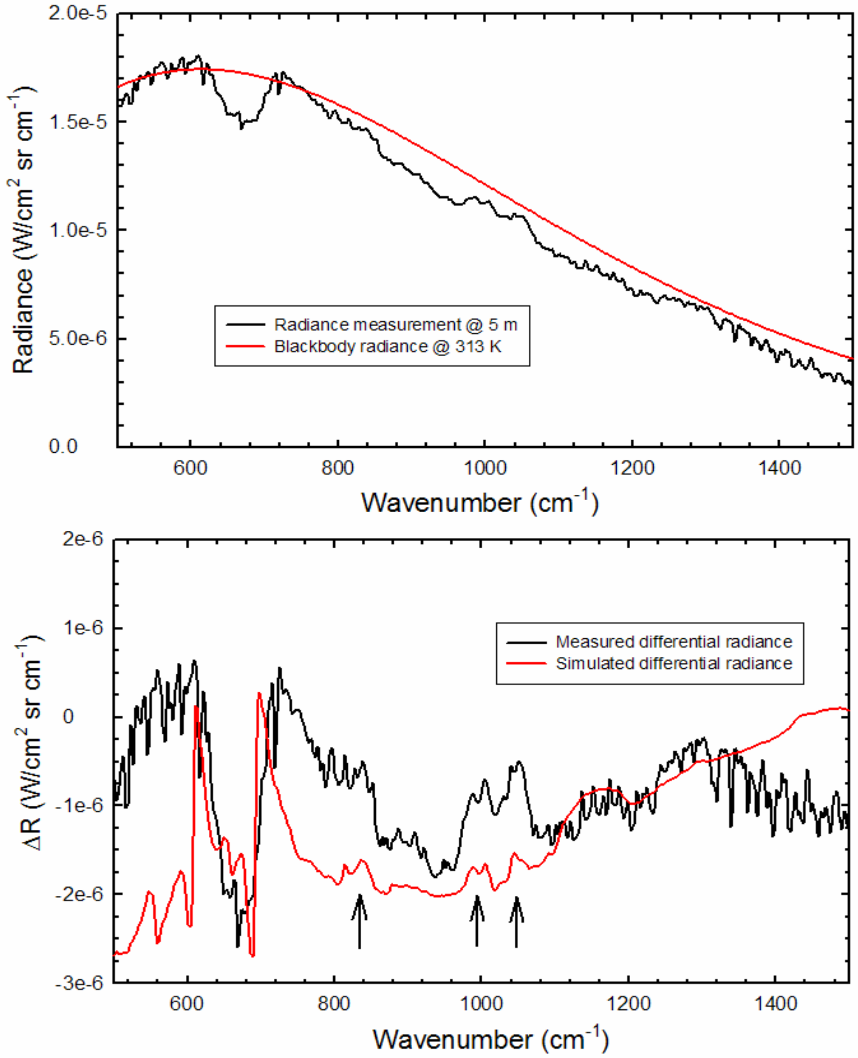

Figure 7. Direct radiance spectra (upper figure) and differential radiance spectra (lower figure) measured and simulated for cobalt oxide. Features denoted by the arrows show the presence of the cobalt oxide fingerprint that may be used for identification purposes.

6. Future Work

The configuration problem involving the MCT detector and the narrow field of view telescope has been resolved recently. As a result, we hope to have another opportunity in 2006/2007 to measure similar radiological materials with the AIRIS sensor onboard the Convair aircraft. In addition, other research activities are planned for next year as outlined below:

(1) In collaboration with DRDC Ottawa, a field trial is planned for Spring 2006 at DRDC Ottawa that will involve the use of ground-based passive standoff FTIR radiometry for detecting and identifying UO2 and U3O8 radioactive materials at standoff distances of 30 and 100 m. This will be the first time that actual radioactive materials have been measured in the open using the passive remote sensing radiometric technique.

(2) In a potential collaboration with Cameco Corp., several uranium oxide materials (including processed and non-processed uranium ores) and waste materials from the milling and processing operations will be measured using passive thermal radiometry and VNIR and SWIR spectroscopic techniques. These ground-based measurement results will be analysed to determine the possibility of using these sensing techniques for the detection and identification of materials specific to uranium mining processes. Laboratory measurements of these materials, including UF6, will also be attempted to characterize their signatures.

(3) If funding is available, the AIRIS sensor will be deployed to measure radiological materials at altitudes of 1 km. The availability of the AIRIS sensor is subject to budgetary approval from another program.

(4) Various national/international meetings and workshops to support further development of the passive remote sensing FTIR technique.

7. Conclusions

Over the past year DRDC Valcartier has continued to investigate the feasibility of using passive standoff FTIR radiometry for the detection of radiological materials. Previously, we have shown that a large number of radiological materials have an infrared signature in the 8–14 μm thermal infrared region, including several oxides of uranium and cobalt. Based on the positive results of a number of ground-based measurements and simulations using the MODTRAN4 atmospheric transmission model, it was decided that a measurement campaign should be attempted using an airborne HSI sensor.

The AIRIS sensor, developed by DRDC Valcartier and installed in a Convair 580 aircraft, was used to measure several radiological compounds from an altitude of 1 km during a trial at DRDC Suffield in July 2005. The ARIS sensor was used in conjunction with two different telescopes; one resulting in high-resolution spatial images and the other resulting in low-spatial resolution images. Unfortunately, the former configuration did not function correctly during the trial, and only the low-resolution images were captured by AIRIS. An additional six months is required for the analysis of these images to be completed before it will be known if the HSI sensor was successful in detecting and identifying the radiological compounds. Ground-truth data collected during the trial at DRDC Suffield will be used in the image analysis process.

Future work is planned for 2006/2007 that may involve an additional trial with the AIRIS HSI sensor.

8. References

1. J.-M. Thériault, E. Puckrin, F. Bouffard and B. Déry, Passive remote monitoring of chemical vapours by differential FTIR radiometry: results at a range of 1.5 km, Appl. Opt., **43**, 1425-1434 (2004).

2. C.T. Chaffin, T.L. Marshall, N.C. Chaffin, Passive FT-IR remote sensing of smokestack emissions, Field Analytical Chemistry and Technology, **3**, 111-115 (1999).

3. D.F. Flanigan, Hazardous cloud imaging: a new way of using passive infrared, Appl. Opt. **36**, 7027-7036 (1997).

4. G. Laufer and A. Ben-David, Optimized differential absorption radiometer for remote sensing of chemical effluents, Appl. Opt. **41**, 2263-2273 (2002).

5. J.-M. Thériault and E. Puckrin, Passive Standoff Detection of BG Aerosol by FTIR Radiometry, Appl. Opt., **42**, 6696-6705 (2003).

6. A. Ben-David, Remote detection of biological aerosols at a distance of 3 km with a passive Fourier transform infrared (FTIR) sensor, Opt. Express, **11**, 418-429 (2003).

7. J.-M. Thériault, E. Puckrin, J. Hancock, P. Lecavalier, Carmela Jackson Lepage and J.O. Jensen, Passive standoff detection of chemical warfare agents on surfaces, Appl. Opt., **43**, 5870-5885 (2004).

8. E. Puckrin and J.-M. Thériault and Q.S.B. Truong, *Detection of Nuclear Materials by Fourier-transform Infrared Spectroscopy*, INMM Annual Meeting, Orlando, 8 pp., 18-22 July 2004.

9. E. Puckrin, J.-M. Thériault, H. Lavoie, J. Lévesque and Q.S. Bob Truong, Recent Advances in the Remote Sensing of Radiological Materials by Passive FTIR Radiometry, 46th Annual Meeting of the Institute of Nuclear Materials Management, 8 pp., Phoenix, AZ, 10-14 July 2005.

10. G.P. Anderson, A. Berk, L.S. Bernstein, J.H. Chetwynd, P.K. Acharya, H. Dothe, M.W. Matthew, S.M. Adler-Golden, R.J. Ratkowski, G.W. Felde, J.A. Gardner, M.L. Hoke, S.C. Richtsmeier, B. Pukall, J. Mello, and L.S. Jeong, MODTRAN4: Radiative transfer modeling for remote sensing and atmospheric correction, *Proc., EUROPTO Remote Sensing Congress*, Florence, Italy (1999).

This page intentionally left blank.

Distribution list

INTERNAL

DRDC Valcartier TN 2006-120

1 -	Director General
3 -	Document Library
1 -	J.-M. Thériault (author)
1 -	E. Puckrin (author)

EXTERNAL DISTRIBUTION

DRDC Valcartier TN 2006-120

1 - DRDKIM (PDF file)

1- Dr. Bob Truong
Canadian Safeguards Support Program
Office of International Affairs
Canadian Nuclear Safety Commission
280 Slater Street
Ottawa, ON, Canada
K1P 5S9

DOCUMENT CONTROL DATA

1. ORIGINATOR (name and address) Eldon Puckrin, DRDC Valcartier	2. SECURITY CLASSIFICATION (Including special warning terms if applicable)

3. TITLE (Its classification should be indicated by the appropriate abbreviation (S, C, R or U)

(U) Recent advances in the remote sensing of radiological materials by passive FTIR radiometry: 2005-2006 summary report

4. AUTHORS (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Puckrin, Eldon. Thériault, Jean-Marc (DRDC Valcartier)

5. DATE OF PUBLICATION (month and year) May 2006	6a. NO. OF PAGES 17	6b. NO. OF REFERENCES 10

7. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. Give the inclusive dates when a specific reporting period is covered.)

This document is submitted to become a DRDC Valcartier Technical Note

8. SPONSORING ACTIVITY (name and address)

DRDC

9a. PROJECT OR GRANT NO. (Please specify whether project or grant) 0470-1804-71223N	9b. CONTRACT NO.
10a. ORIGINATOR'S DOCUMENT NUMBER TN 2006-120	10b. OTHER DOCUMENT NOS N/A

11. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

- ☒ Unlimited distribution
- ☐ Contractors in approved countries (specify)
- ☐ Canadian contractors (with need-to-know)
- ☐ Government (with need-to-know)
- ☐ Defense departments
- ☐ Other (please specify)

12. DOCUMENT ANNOUNCEMENT (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in 11) is possible, a wider announcement audience may be selected.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual).

N/A

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus-identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Passive standoff detection, radiological, dirty bomb, radiological dispersion device, FTIR radiometry

Defence R&D Canada

Canada's leader in defence
and national security R&D

R & D pour la défense Canada

Chef de file au Canada en R & D
pour la défense et la sécurité nationale

DEFENCE R&D DÉFENSE

WWW.drdc-rddc.gc.ca